STUDENT WORKBOOK

QNET VTOL Trainer for NI ELVIS

Developed by Quanser

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Contents

1 INTRODUCTION

The QNET vertical take-off and landing (VTOL) trainer is shown in Figure 1.1. The system consists of a variable-speed fan with a safety guard mounted on an arm. At the other end of the arm, an adjustable counterweight is attached. This allows the position of the weight to be changed, which in turn affects the dynamics of the system. The arm assembly pivots about a rotary encoder shaft. The VTOL pitch position can be acquired from this setup.

Some examples of real-world VTOL devices are helicopters, rockets, balloons, and harrier jets. Aerospace devices are typically more difficult to model. Usually this will involve using software system identification tools to determine parameters or actual dynamics. Due to their inherent complexity, flight systems are usually broken down into different subsystems to make it more manageable. These subsystems can be dealt with individually and then integrated to provide an overall solution.

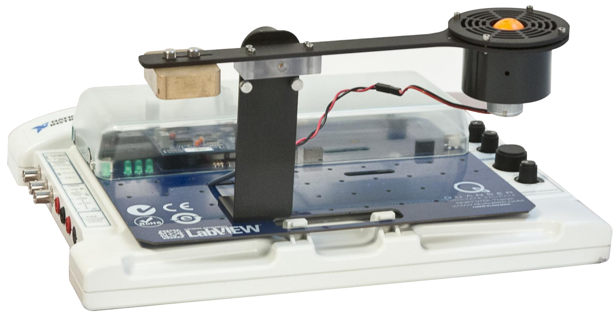


Figure 1.1: QNET Vertical Take-off and Landing Trainer (VTOL)

There are three experiments: current control, modeling, and flight control. The experiments can be performed independently.

Topics Covered

- Experimental Modelling
- PID Control
- Current Control
- Pitch Control

Prerequisites
In order to successfully carry out this laboratory, the user should be familiar with the following:

- Transfer function fundamentals, e.g. obtaining a transfer function from a differential equation.
- Using LabVIEW®to run VIs.

2 CURRENT CONTROL

2.1 Background

2.1.1 Cascade Control

The VTOL device is broken down into two subsystems: the voltage-current dynamics of the motor and the current-position dynamics of the VTOL body. The cascade control implemented in the VTOL trainer is depicted in Figure 2.1, below. A PI current controller, the inner loop, is designed to regulate the current inside the motor according to a desired current reference. This current reference is generated from the outer-loop controller: a PID compensator that controls the pitch of the VTOL trainer.

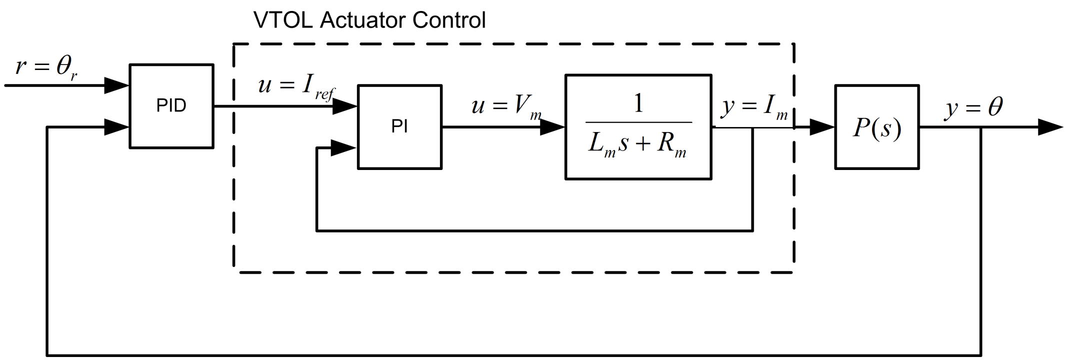


Figure 2.1: VTOL trainer cascade control system

2.1.2 Current Control

In cases where the actuator has relatively slow dynamics, such as an electromagnet with a large inductance, it is favorable to design a current controller. Typically a proportional-integral compensator is used to regulate the current flowing in the load. This basically makes the actuator dynamics negligible and simplifies the control design of the outer-loop.

In this case, the voltage-current relationship of the VTOL trainer motor can be described, in the time-domain, by the equation

$$v_m = R_m i_m + L_m \dot{i}_m$$

and by the transfer function

$$I_m(s) = \frac{V_m(s)}{R_m + L_m s}$$

Figure 2.2 shows the VTOL current control system implemented. The PI compensator computes the voltage necessary to reach the desired current.

Using the PI controller

$$v_m(t) = k_{p,c}(i_{ref}(t) - i_m(t)) + k_{i,c} \int i_{ref}(t) - i_m(t)\, dt$$

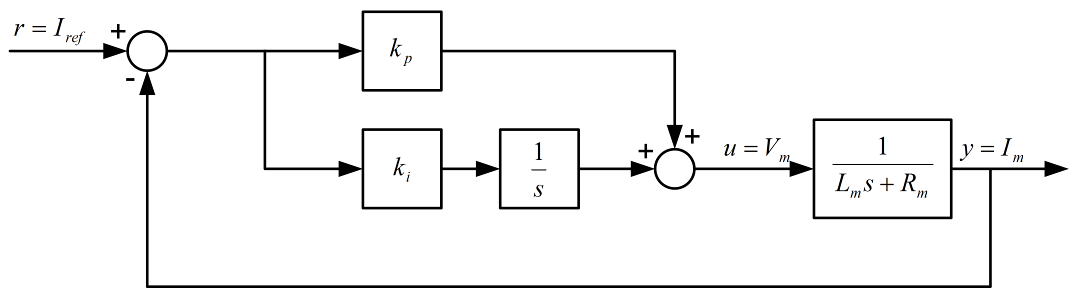


Figure 2.2: VTOL motor PI current control loop

we obtain the following closed-loop transfer function

$$G_{I_{ref},I_m}(s) = \frac{k_{p,c}s + k_{i,c}}{s^2 L_m + (k_{p,c} + R_m)s + k_{i,c}}$$

To match the standard *second-order characteristic equation*

$$s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (2.1)$$

we need a proportional gain of

$$k_{p,c} = -R_m + 2\zeta\omega_n L_m \quad (2.2)$$

and an integral gain of

$$k_{i,c} = \omega_n^2 L_m \quad (2.3)$$

These gains can then be designed according to a desired natural frequency, ω_n, and damping ratio, ζ.

2.2 Current Control Virtual Instrument

In this laboratory, open-loop voltage or current is fed to the VTOL trainer. In current mode, shown in Figure 2.3, a current-controller is used to regulate the current in the motor and the user chooses the reference current. In voltage mode, shown in Figure 2.4, the voltage chosen is applied directly to the QNET amplifier, which in turn drives the motor.

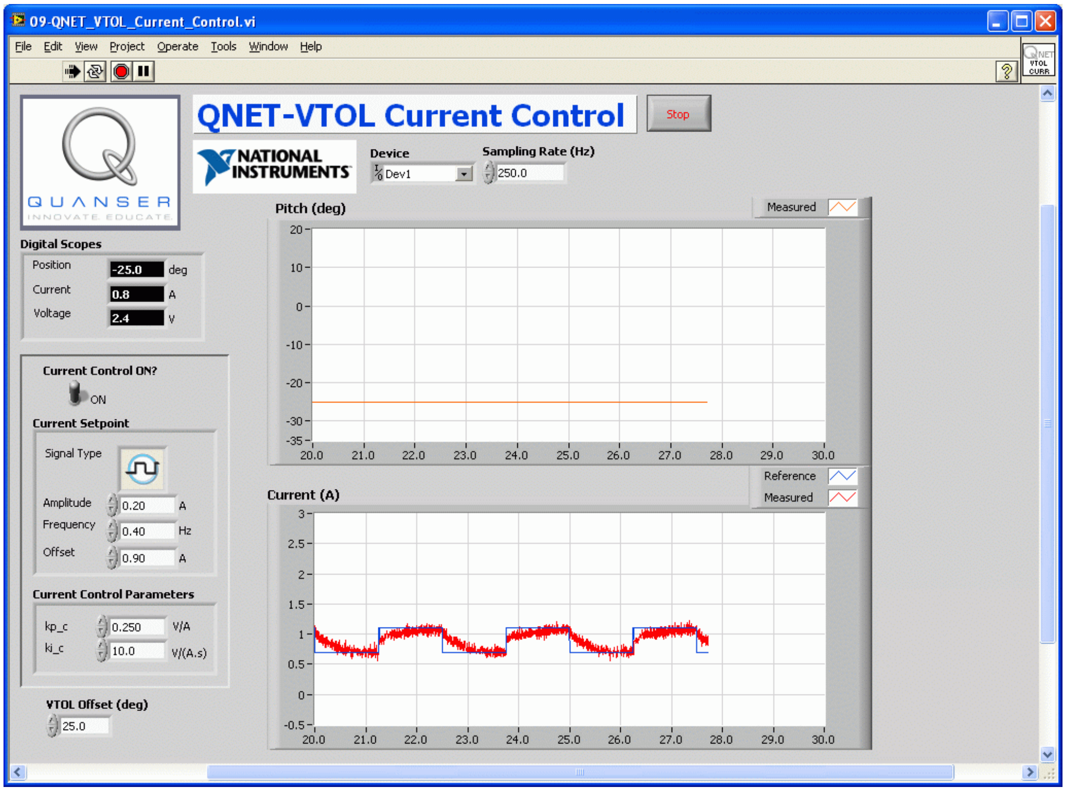


Figure 2.3: Virtual Instrument for VTOL current control

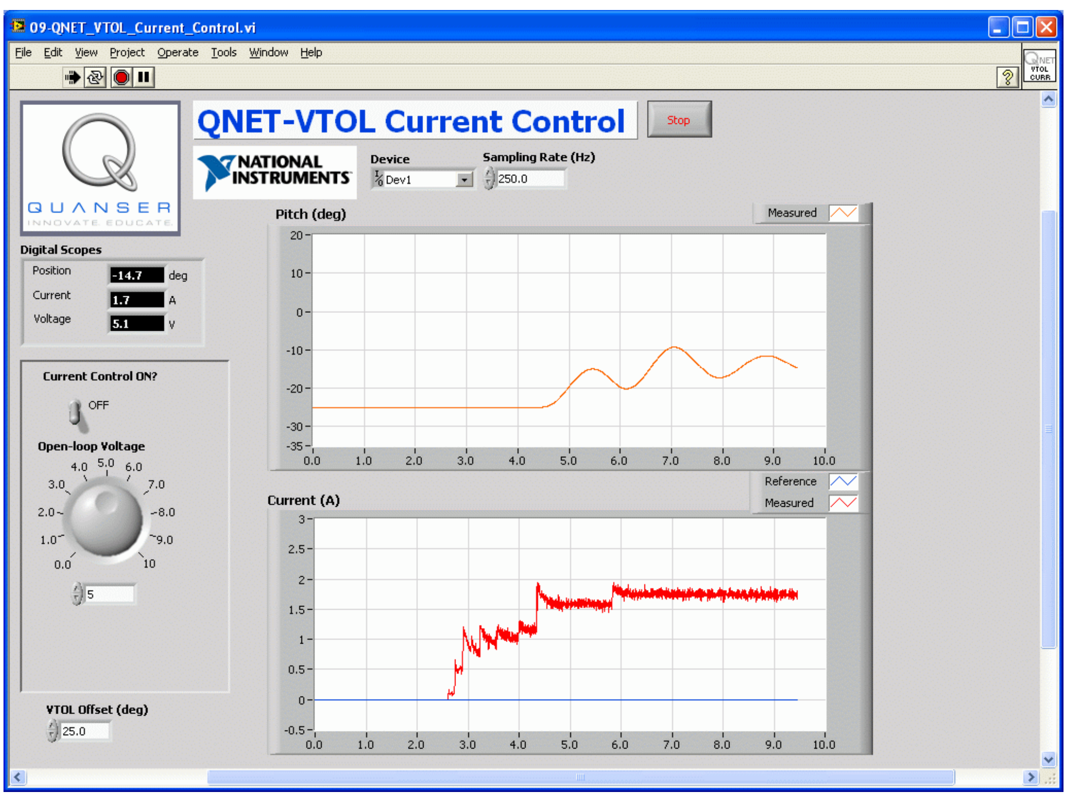


Figure 2.4: Virtual Instrument for VTOL voltage control

2.3 Lab 1: Finding Resistance

1. Ensure the QNET VTOL Current Control VI is open and configured as described in Section 5.2. **Make sure the correct *Device* is chosen.**
2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself*. The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 2.5.

Figure 2.5: VTOL initial position

3. Run the QNET_VTOL_Current_Control.vi.
4. Set the *Current Control ON?* switch to OFF.
5. Set the *Open-loop Voltage* knob to 4.0 V. The VTOL Trainer propeller should begin turning as a voltage is applied to the motor.
6. Vary the voltage between 4.0 and 8.0 V by steps of 1.0 V and measure the current at each voltage.

Input Voltage (V)	Measured Current (A)	Resistance (ω)
4		
5		
6		
7		
8		
Average Resistance: $R_{m,avg}$		

Table 2.1: QNET VTOL Finding Resistance

7. Click on *Stop* button to stop the VI.

2.4 Lab 2: Qualitative Current Control

1. Ensure the QNET VTOL Current Control VI is open and configured as described in Section 5.2. **Make sure the correct *Device* is chosen.**
2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself*. The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 2.5.

3. Set the *Current Control ON?* switch to ON.
4. Run the QNET_VTOL_Current_Control.vi.
5. In the *Current Setpoint* section set:
   - Amplitude = 0.20 A
   - Frequency = 0.40 Hz
   - Offset = 0.90 A
6. In the *6. Control Parameters* section set the PI current gains to:
   - $k_{p,c}$ = 0.250
   - $k_{i,c}$ = 10

   The VTOL Trainer propeller should begin turning at various speeds according to the current command. Examine the reference and measured current response obtained in the Current (A) scope. They should be tracking as shown in Figure 2.3.
7. Show and explain the effect of not having any integral gain. Attach a sample response.
8. In the *Control Parameters* section set the PI current gains to:
   - k_p, c = 0
   - k_i, c = 100
9. Show and explain the effect of not having any proportional gain. Attach a sample response.
10. Click on Stop button to stop the VI.

2.5 Lab 3: Current Control Design

2.5.1 Pre-Lab Exercises

1. Calculate the PI gains, k_p and k_i, necessary to satisfy the natural frequency and damping ratio specifications:
   - ω_n = 42.5 rad/s
   - ζ = 0.70

   To compute the gains, you will need the resistance found in Section 2.3 and assume the inductance of the motor is L_m = 53.8 mH.

2.5.2 In-Lab Experiment

1. Open the QNET_VTOL_Current_Control.vi as shown in Section 5.2. **Make sure the correct *Device* is chosen.**
2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself*. The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 2.5.
3. Set the *Current Control ON?* switch to *ON*.
4. In the *Current Setpoint* section set:
   - Amplitude = 0.20 A
   - Frequency = 0.40 Hz
   - Offset = 0.90 A

5. In the *Current Control Parameters* section, set the PI current gains to those you found in Section 2.5.1.
6. Run the VI. The VTOL Trainer propeller should begin turning at various speeds according to the current command. Examine the reference and measured current response obtained in the *Current (A)* scope. They should be tracking.
7. Include a plot showing the current response with your designed PI gains. Compare the response to the qualitative responses in Section 2.4.
8. Click on *Stop* button to stop the VI.

2.6 Results

Parameter	Value	Units
R_m		ω
L_m		mH
ζ		
ω_n		rad/s
$k_{p,c}$		V/A
$k_{i,c}$		V/(A s)

Table 2.2: PI current control design summary

3 MODELING

3.1 Background

Unlike a DC motor, this system has to be characterized with at least a second-order model. The equation of motion is derived from first principles and then used to obtain the transfer function representing the current to position VTOL dynamics.

Various methods can be used to find the modeling parameters. In the laboratory, the parameters are first found manually by performing a few experiments and taking measurements. Thereafter, the LabVIEW® *System Identification Toolkit* is used to automatically find the model. This demonstrates how to use software tools to identify parameters or even entire models (especially important for higher-order systems). The modeling is then validated by running the obtained model in parallel with the actual system.

3.1.1 Torques Acting on the VTOL

The free-body diagram of a 1-DOF Vertical Take-Off and Landing device that pivots about the pitch axis is shown in Figure 3.1.

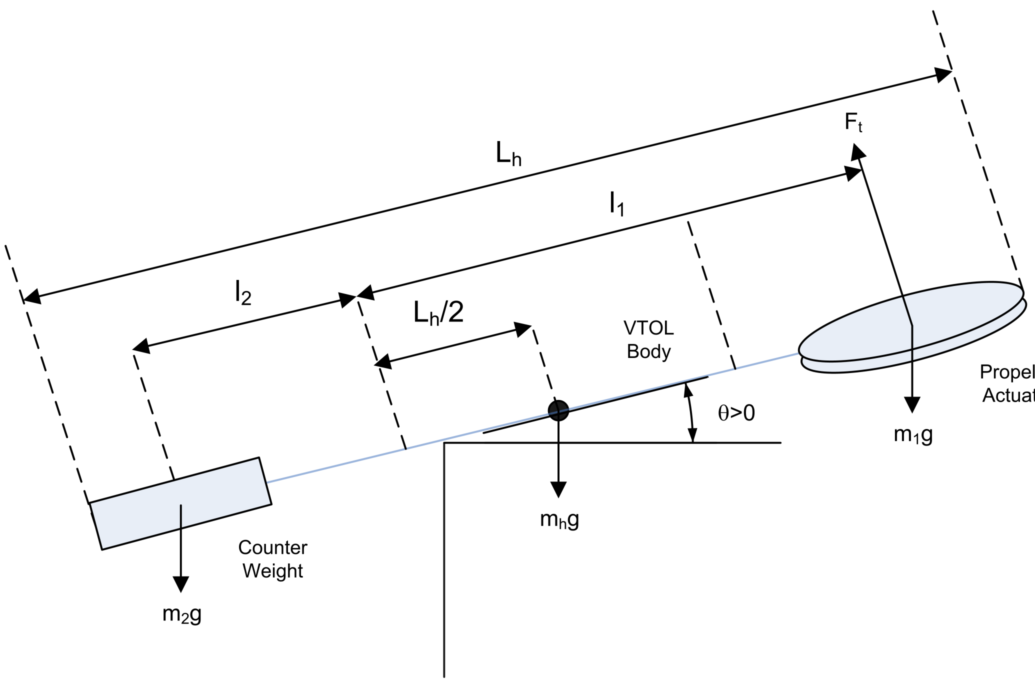


Figure 3.1: Free-body diagram of 1-DOF VTOL

As shown in Figure 3.1, the torques acting on the rigid body system can be described by the equation

$$\tau_t + m_2\, g\, l_2 \cos\theta(t) - m_1\, g\, l_1 \cos\theta(t) - \frac{1}{2}\, m_h\, g\, L_h \cos\theta(t) = 0 \tag{3.1}$$

The thrust force, F_t, is generated by the propeller and acts perpendicular to the fan assembly. The thrust torque is given by

$$\tau_t = F_t\, l_1 \tag{3.2}$$

where l_1 is the length between the pivot and center of the propeller, as depicted in Figure 3.1. In terms of the current, the thrust torque equals

$$\tau_t = K_t \, I_m \tag{3.3}$$

where K_t is the thrust current-torque constant. With respect to current, the torque equation becomes

$$K_t \, I_m + m_2 \, g \, l_2 \cos \theta(t) - m_1 \, g \, l_1 \cos \theta(t) - \frac{1}{2} m_h \, g \, L_h \cos \theta(t) = 0 \tag{3.4}$$

The torque generated the propeller and the gravitational torque acting of the counter-weight act in the same direction and oppose the gravitational torques on the helicopter body and propeller assembly.

We define the VTOL trainer as being in *equilibrium* when the thrust is adjusted until the VTOL is horizontal and parallel to the ground. At equilibrium, the torques acting on the system are described by the equation

$$K_t \, I_e q + m_2 \, g \, l_2 - m_1 \, g \, l_1 - \frac{1}{2} m_h \, g \, L_h = 0 \tag{3.5}$$

where $I_e q$ is the current required to reach equilibrium.

3.1.2 Equation of Motion

The angular motions of the VTOL trainer with respect to a thrust torque, τ_t, can be expressed by the equation

$$J \, \ddot{\theta} + B \, \dot{\theta} + K \, \theta = \tau_t \tag{3.6}$$

where θ is the pitch angle, J is the equivalent moment of inertia acting about the pitch axis, B is the viscous damping, and K is the stiffness. With respect to current, this becomes

$$J \, \ddot{\theta} + B \, \dot{\theta} + K \, \theta = K_t \, I_m \tag{3.7}$$

As opposed to finding the moment of inertia by integrating over a continuous body, when finding the moment of inertia of a composite body with n point masses its easiest to use the formula

$$J = \sum_{i=1}^{n} m_i \, r_i^2 \tag{3.8}$$

3.1.3 Process Transfer Function Model

The transfer function representing the current to position dynamics of the VTOL trainer is

$$P(s) = \frac{K_t}{J \left(s^2 + \frac{B}{J} s + \frac{K}{J} \right)} \tag{3.9}$$

This is obtained by taking the Laplace transform of Equation 3.6 and solving for $\Omega(s)/I_m(s)$. Notice that the denominator

$$s^2 + \frac{B}{J}s + \frac{K}{J}$$

matches the characteristic second-order transfer function Equation 2.1. By determining the natural frequency of the system, one can find the stiffness using

$$K = \omega_n^2 J \qquad (3.10)$$

3.2 Modeling Virtual Instrument

The virtual instrument used to validate a transfer function model on the QNET VTOL trainer is shown in Figure 3.2. This VI can also be used to find the VTOL device transfer function using the *System Identification Toolkit*.

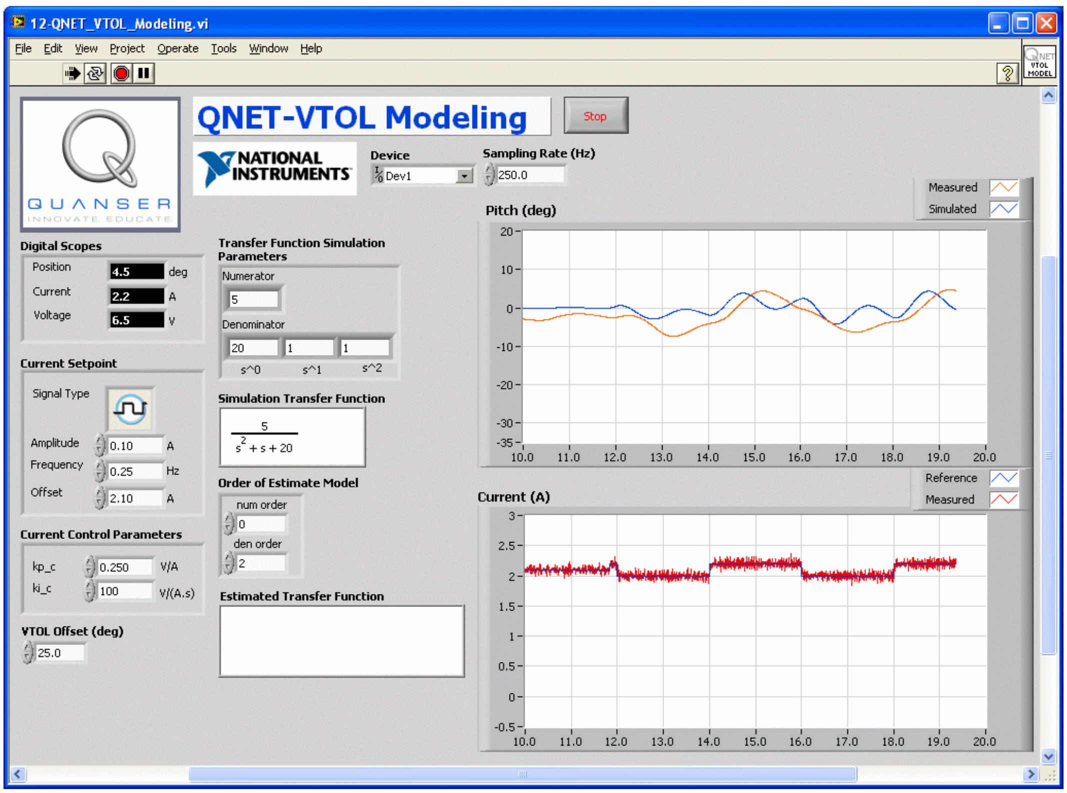


Figure 3.2: LabVIEW virtual instrument used to find and validate a model for the QNET VTOL trainer

3.3 Lab 1: Measure the Equilibrium Current

1. Ensure the QNET VTOL Current Control VI is open and configured as described in Section 5.2. **Make sure the correct *Device* is chosen.**

2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself*. The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 3.3.

Figure 3.3: VTOL initial position

3. Set the *Current Control ON?* switch to *ON*.
4. Run the VI.
5. In the *Current Control Parameters* section, set the PI current gains found in the first part of Section 2.5.
6. In the *Current Setpoint* section set:
   - Amplitude = 0.00 A
   - Frequency = 0.40 Hz
   - Offset = 1.00 A
7. Gradually increase the offset current until the VTOL Trainer is horizontal.
8. The pitch should read 0 degrees when the VTOL Trainer is horizontal. You may need to adjust the pitch offset by varying the *VTOL Offset* control. By default this is set to 25.0 degrees.
9. The current required to make the VTOL Trainer horizontal is called the equilibrium current, I_{eq}. Capture the pitch and current response and record this current.
10. Click on *Stop* button to stop the VI.

3.4 Lab 2: Find Natural Frequency

1. Ensure the QNET VTOL Current Control VI is open and configured as described in Section 5.2. **Make sure the correct *Device* is chosen.**
2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself*. The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 3.3.
3. Set the *Current Control ON?* switch to *ON*.
4. In the *Current Control Parameters* section, set the PI current gains found in Section 2.5.
5. In the Current Setpoint section set:
   - Amplitude = 0.00 A
   - Frequency = 0.40 Hz
   - Offset = I_{eq} (equilibrium current found in Section 3.3)
6. Run the VI.

7. When the VI starts and the equilibrium current step is applied, the VTOL Trainer will shoot upwards quickly and then oscillate about its horizontal. Capture this response and measure the natural frequency.
8. Click on Stop button to stop the VI.

3.5 Lab 3: Model Validation

3.5.1 Pre-Lab Exercises

1. Using the VTOL Trainer model given in Section 3.1.2, and the specifications listed in the *VTOL User Manual* [1], compute the moment of inertia acting about the pitch axis. Enter the value in Table 3.1.
2. Based on the natural frequency found in Section 3.4 and the moment of inertia calculated above, find the stiffness of the VTOL Trainer. Enter the value in Table 3.1.
3. Using the equations presented in Section 3.1 and the equilibrium current found in Section 3.3, calculate the thrust current-torque constant K_t. Enter the value in Table 3.1.
4. Compute the VTOL Trainer transfer function coefficients based on the previously found parameters: K_t, J, B, and K.

3.5.2 In-Lab Experiment

1. Ensure the QNET VTOL Modelling VI is open and configured as described in Section 5.3. **Make sure the correct *Device* is chosen.**
2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself*. The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 3.3.
3. In the *Current Control Parameters* section, set the PI current gains found in Section 2.5.
4. In the Current Setpoint section set:
   - Amplitude = 0.00 A
   - Frequency = 0.20 Hz
   - Offset = I_{eq} (equilibrium current found in Section 3.3)
5. Run the VI.
6. Let the VTOL Trainer stabilizes about the horizontal.
7. In the *Current Setpoint* section set:
   - Amplitude =0.10 A
8. In the *Transfer Function Simulation Parameters* section, enter the parameters computed in Section 3.5.1. Is the simulation matching the measured signal? Capture the response.
9. Click on Stop button to stop the VI.

3.6 Lab 4: Using the System Identification Tool

1. Ensure the QNET VTOL Modelling VI is open and configured as described in Section 5.3. **Make sure the correct *Device* is chosen.**

2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself.* The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 3.3.

3. in the *Current Setpoint* section set:

   - Amplitude = 0.10 A
   - Frequency = 0.20 Hz
   - Offset = I_{eq} (equilibrium current found in Section 3.3)

   which should perturb the VTOL Trainer is about its horizontal equilibrium point with a current amplitude of +/- 0.10 A, as described by steps 4-10 in Section 3.5.

4. Let the VI run for at least 20 seconds.

5. Click on *Stop* button to stop the VI. When the VI is stopped, the *Estimated Transfer Function* displays a newly identified transfer function of the VTOL system based on the last 20 seconds of current (i.e. stimulus signal) and pitch angle (i.e. response signal) data.

6. Enter the identified transfer function.

7. Enter the identified TF parameters into the *Transfer Function Simulation Parameters* section.

8. Go through steps 7-10 in Section 3.5. That is, bring the VTOL Trainer up to 0 degrees and then feed +/- 0.1 A.

9. In the *Transfer Function Simulation Parameters* section, enter the parameters computed using the System Identification Tool. How is the simulation matching the measured signal compared to the transfer function with the manually estimated parameters? Capture the response.

10. Click on Stop button to stop the VI.

11. Assume the moment of inertia is as calculated in Section 3.5. Then from the identified transfer function, find the stiffness ($K_i d$), the viscous damping ($B_i d$), and the current-torque constant ($K_{t,id}$). How do they compare with the parameters you estimated manually?

3.7 Results

Parameters	Symbol	Value	Units
Equilibrium current	I_{eq}		A
Torque-thrust constant	K_t		(N m)/A
Moment of inertia	J		kg m^2
Viscous damping	B		(N m s)/rad
Natural frequency	ω_n		rad
Stiffness	K		(N m)/rad
Sys ID: Torque-thrust constant	$K_{t,id}$		(N m)/A
Sys ID: Viscous damping	B_{id}		(N m s)/rad
Sys ID: Stiffness	K_{id}		(N m)/rad

Table 3.1: VTOL Trainer modeling results summary

4 FLIGHT CONTROL

4.1 Background

4.1.1 Steady-state Error Analysis

Steady-state error is the difference between the reference and output signals after the system response has settled. Thus for a time t when the system is in steady-state, the steady-state error equals

$$e_{ss} = r_{ss}(t) - y_{ss}(t) \tag{4.1}$$

where r_{ss} is the value of the steady-state reference and y_{ss} is the steady-state value of the process output.

The block diagram shown in Figure 4.1 is a general unity feedback system with a compensator $C(s)$ and a transfer function representing the plant, $P(s)$. The measured output, $Y(s)$, is supposed to track the reference signal $R(s)$ and the tracking has to yield to certain specifications.

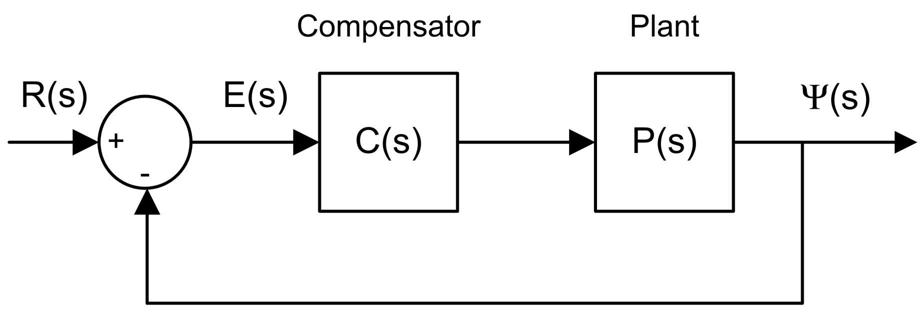


Figure 4.1: Unity feedback system.

The error of the system shown in Figure 4.1 is

$$E(s) = R(s) - Y(s)$$

and by solving for $E(s)$ the resulting closed-loop transfer function

$$E(s) = \frac{R(s)}{1 + C(s)P(s)}$$

is obtained.

The error transfer function of the VTOL trainer when subject to a step of

$$R(s) = \frac{R(0)}{s}$$

and using the PID compensator

$$C(s) = k_p + k_d s + \frac{k_i}{s}$$

is

$$E(s) = \frac{R_0}{s\left(1 + \frac{\left(k_p + k_d s + \frac{k_i}{s}\right) K_t}{J\left(s^2 + \frac{B}{J}s + \frac{K}{J}\right)}\right)}$$

If the transfer function is stable, then the steady-state error can be found using the final-value theorem (FVT)

$$e_{ss} = \lim_{s \to 0} sE(s)$$

Using FVT, the steady-state error of the VTOL trainer closed-loop PID step response is

$$e_{ss} = R_0 \left(\lim_{s \to 0} \frac{s(s^2 J + Bs + K)}{s^3 J + Bs^2 + K_t k_d s^2 + sK + K_t k_p s + K_t k_i} \right) \quad (4.2)$$

4.1.2 PID Control Design

The PID control loop used for the VTOL device is depicted in Figure 4.2

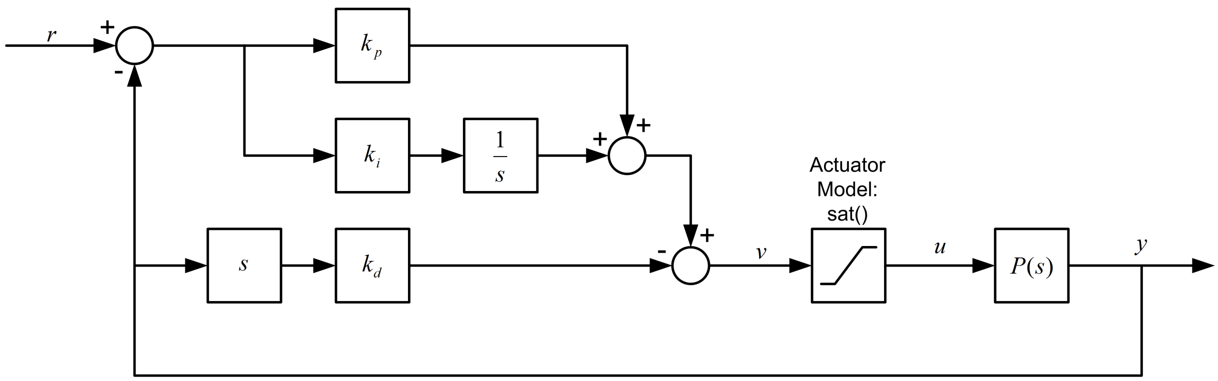


Figure 4.2: VTOL PID Control Loop

The transfer function representing the VTOL trainer position-current relation in Equation 3.9 is used to design the PID controller. The input-output relation in the time-domain for a PID controller is

$$u = k_p(\theta_d - \theta) + k_i \int (\theta_d - \theta)\, dt - k_v\, \dot{\theta} \quad (4.3)$$

where k_p is the proportional gain, k_i is the integral gain, and k_v is the velocity gain. Remark that only the measured velocity is used, i.e. instead of using the derivative of the error. The closed loop transfer function from the position reference, r, to the angular VTOL position output, θ, is

$$G_{\theta,r}(s) = \frac{K_t(k_p s + k_i)}{Js^3 + (B + K_t k_v)s^2 + (K + K_t k_p)s + K_t k_i} \quad (4.4)$$

The prototype third-order characteristic polynomial is

$$(s^2 + 2\zeta\omega_n s + \omega_n^2)(s + p_0) = s^3 + (2\zeta\omega_n + p_0)s^2 + (\omega_n^2 + 2\zeta\omega_n p_0)s + \omega_n^2 p_0 \tag{4.5}$$

where ω_n is the natural frequency, ζ is the damping ratio, and p_0 is a zero.

The characteristic equation in Equation 4.4 (the denominator of the transfer function), can match the desired characteristic equation Equation 4.5 with the following gains

$$k_p = \frac{-K + 2p_0\zeta\omega_n J + \omega_n^2 J}{K_t} \tag{4.6}$$

$$k_i = \frac{p_0\omega_n^2 J}{K_t} \tag{4.7}$$

$$k_v = \frac{-B + p_0 J + 2\zeta\omega_n J}{K_t} \tag{4.8}$$

4.2 Flight Control Virtual Instrument

The virtual instrument used to run the flight controller on the QNET VTOL trainer is shown in Figure 4.3.

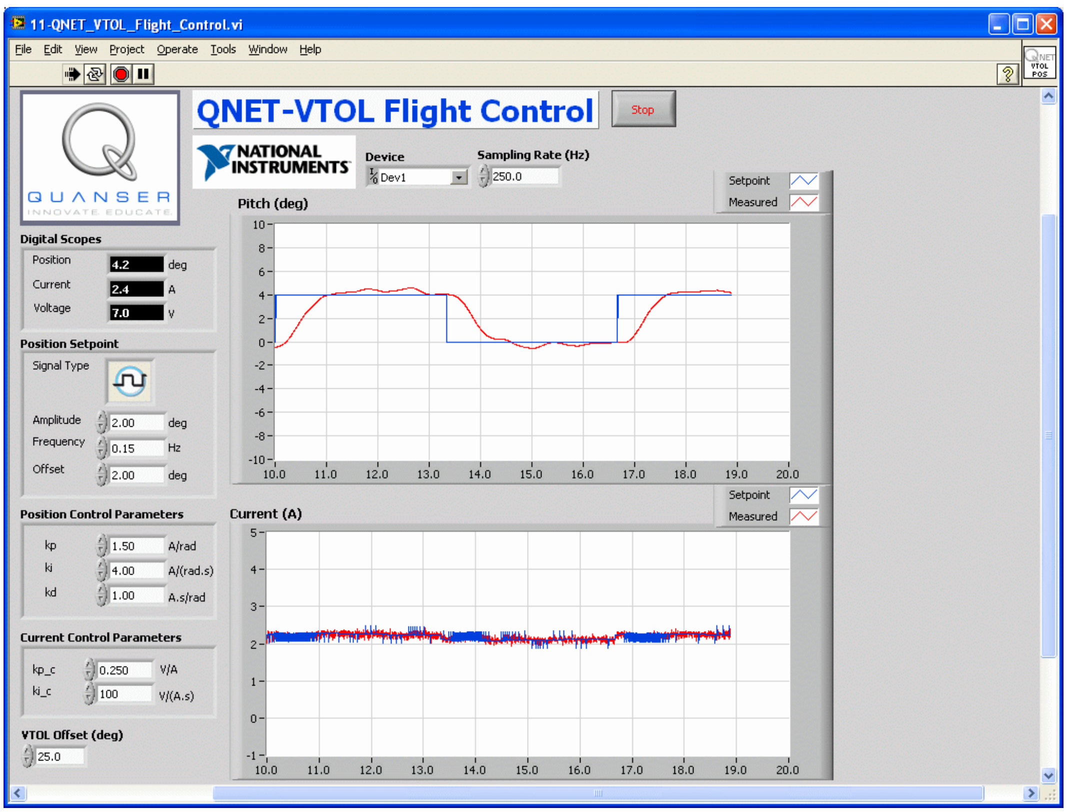


Figure 4.3: LabVIEW virtual instrument used to run VTOL trainer flight control

4.3 Lab 1: PD Steady-State Analysis

4.3.1 Pre-Lab Exercises

1. Calculate the theoretical VTOL Trainer steady-state error when using a PD control with k_p = 2 and k_d = 1 and a step amplitude of R_0 = 4.0 degrees. Enter the value in Table 4.1.

4.3.2 In-Lab Experiment

1. Open the QNET_VTOL_Flight_Control.vi as shown in Section 5.4. **Make sure the correct *Device* is chosen.**
2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself*. The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 4.4.

Figure 4.4: VTOL initial position

3. Run the VI
4. In the *Position Setpoint* section set:
   - Amplitude = 0.0 deg
   - Frequency = 0.15 Hz
   - Offset = 0.0 deg
5. In the *Position Control Parameters* section set:
   - kp = 1.0 A/rad
   - ki = 2 A/(rad·s)
   - kd = 1.0 A·s/rad
6. Let the VTOL system stabilize about the 0.0 rad setpoint. Examine if the VTOL Trainer body is horizontal. If not, then you can adjust the pitch offset by varying the VTOL Offset control. By default this is set to 25.0 degrees.
7. To use a PD control, in the *Position Control Parameters* section set:
   - kp = 2.0 A/rad
   - ki = 0 A/(rad.s)
   - kd = 1.0 A.s/rad

8. In the *Position Setpoint* section set:

   - Amplitude = 2.0 deg
   - Frequency = 0.40 Hz
   - Offset = 2.0 deg

   The VTOL Trainer should be going up and down and tracking the square wave setpoint.

9. Capture the VTOL device step response when using this PD controller and measure the steady-state error. Enter the measured PD steady-state error value in Table 4.1. How does it compare with the computed value in Section 4.3.1?

10. In the *Signal Generator* section set *Amplitude (rad)* to 0 rad and slowly decrement *Offset (rad)* to -8.0 rad.

11. Click on the *Stop* button to stop running the VI.

4.4 Lab 2: PID Steady-State Error Analysis

4.4.1 Pre-Lab Exercises

1. Calculate the VTOL Trainer steady-state error when using a PID controller. Enter the value in Table 4.1.

4.4.2 In-Lab Experiment

1. Go through steps 1-8 in Section 4.3.2 to run the PD controller.
2. In the *Position Control Parameters* section, increment the integral gain until you reach k_i = 4.0 A/(rad·s).
3. Capture the VTOL Trainer step response when using a PID controller and measure the steady-state error. Enter the measured PID steady-state error value in Table 4.1. How does it compare with the computed value in Section 4.4.1?
4. To stop the control, in the *Signal Generator* section set *Amplitude (rad)* to 0 rad and slowly decrement *Offset (rad)* to -8.0 rad.
5. Click on the *Stop* button to stop running the VI.

4.5 Lab 3: PID Control Design

4.5.1 Pre-Lab Exercises

1. Find the natural frequency, ω_n, and damping ratio, ζ, required to meet a peak time of 1.0 seconds and a percent overshoot of 20%. Enter the value in Table 4.1.
2. Calculate the PID gains k_p, k_i, and k_v, needed to meet the VTOL Trainer specifications. Enter the value in Table 4.1.

4.5.2 In-Lab Experiment

1. Open the QNET_VTOL_Flight_Control.vi as shown in Section 5.4. **Make sure the correct *Device* is chosen.**
2. Make sure that the VTOL counter-weight is placed as far from the propeller assembly as possible *without lifting the propeller itself*. The base of the propeller assembly should rest lightly on the surface of the QNET board as shown in Figure 4.4.
3. Run the VI
4. In the *Position Setpoint* section set:
    - Amplitude = 0.0 deg
    - Frequency = 0.15 Hz
    - Offset = 0.0 deg
5. In the *Position Control Parameters* section, enter the PID gains found in Section 4.5.1.
6. Let the VTOL system stabilize about the 0.0 rad setpoint. Examine if the VTOL Trainer body is horizontal. If not, then you can adjust the pitch offset by varying the VTOL Offset control. By default this is set to 25.0 degrees.
7. In the *Position Setpoint* section set:

- Amplitude = 2.0 deg
- Frequency = 0.40 Hz
- Offset = 2.0 deg

The VTOL Trainer should be going up and down and tracking the square wave setpoint.

8. Capture the response of the VTOL system when using your designed PID controller.
9. Measure the peak time and percent overshoot of the measured response. Enter the values in Table 4.1. Are the VTOL Trainer response specifications satisfied?
10. If the specifications were not given, what could be done to improve the response?
11. To stop the control, in the *Signal Generator* section set *Amplitude (rad)* to 0 rad and slowly decrement *Offset (rad)* to -8.0 rad.
12. Click on the *Stop* button to stop running the VI.

4.6 Results

Parameters	Symbol	Value	Units
PD steady-state error	$e_{ss,pd}$		deg
Measured PD steady-state error	$e_{ss,meas,pd}$		deg
PID steady-state error	$e_{ss,pid}$		deg
Measured PID steady-state error	$e_{ss,meas,pid}$		deg
Desired peak time	t_p	1.0	s
Desired percentage overshoot	PO	20.0	%
Desired pole location	p_0	1.0	rad/s
Natural frequency	ω_n		rad/s
Damping ratio	ζ		
Proportional gain	k_p		A/rad
Integral gain	k_p		A/(rad s)
Derivative gain	k_v		(A s)/rad
Measured peak time	t_p		s
Measured percentage overshoot	PO		%

Table 4.1: VTOL Trainer control results summary

5 SYSTEM REQUIREMENTS

Required Hardware

- NI ELVIS II
- Quanser QNET Vertical Take-off and Landing (VTOL). See QNET VTOL User Manual ([1]).

Required Software

- NI LabVIEW® 2011 or later
- NI DAQmx 9.3.5 or later
- NI LabVIEW Control Design and Simulation Module 2011 or later
- *ELVIS II Users*: ELVISmx 4.3 or later (installed from ELVIS II CD).

■ **Caution: If these are not all installed then the VI will not be able to run!** Please make sure all the software and hardware components are installed. If an issue arises, then see the troubleshooting section in the QNET VTOL User Manual ([1]).

5.1 Overview of Files

File Name	Description
QNET VTOL User Manual.pdf	This manual describes the hardware of the QNET Vertical Take-off and Landing system and how to setup the system on the ELVIS.
QNET VTOL Lab Manual (Student).pdf	This laboratory guide contains pre-lab questions and lab experiments demonstrating how to design and implement controllers on the QNET VTOL system LabVIEW®.
QNET_VTOL_Current_Control.vi	Control the current in the propeller motor.
QNET_VTOL_Modeling.vi	Validate transfer function model and identify system parameters.
QNET_VTOL_Flight_Control.vi	Control the pitch of the VTOL device using PID.

Table 5.1: Files supplied with the QNET VTOL Laboratory.

5.2 Current Control Laboratory VI

The VTOL Current Control VI, shown in Figure 5.1 and Figure 5.2, is used to feed an open-loop voltage or current to the QNET-VTOL Trainer. The VI when in current mode is shown in Figure 5.1. In this mode, a current-controller is used to regulate the current in the motor and the user chooses the reference current. In voltage mode, shown in Figure 5.2, the voltage chosen is applied directly to the QNET amplifier, which in turn drives the motor. As a quick VI description, Table 5.2 lists and describes the main elements of the QNET VTOL Current Control VI. Every element is uniquely identified by an ID number located in Figure 5.1 and Figure 5.2, for both current and voltage mode.

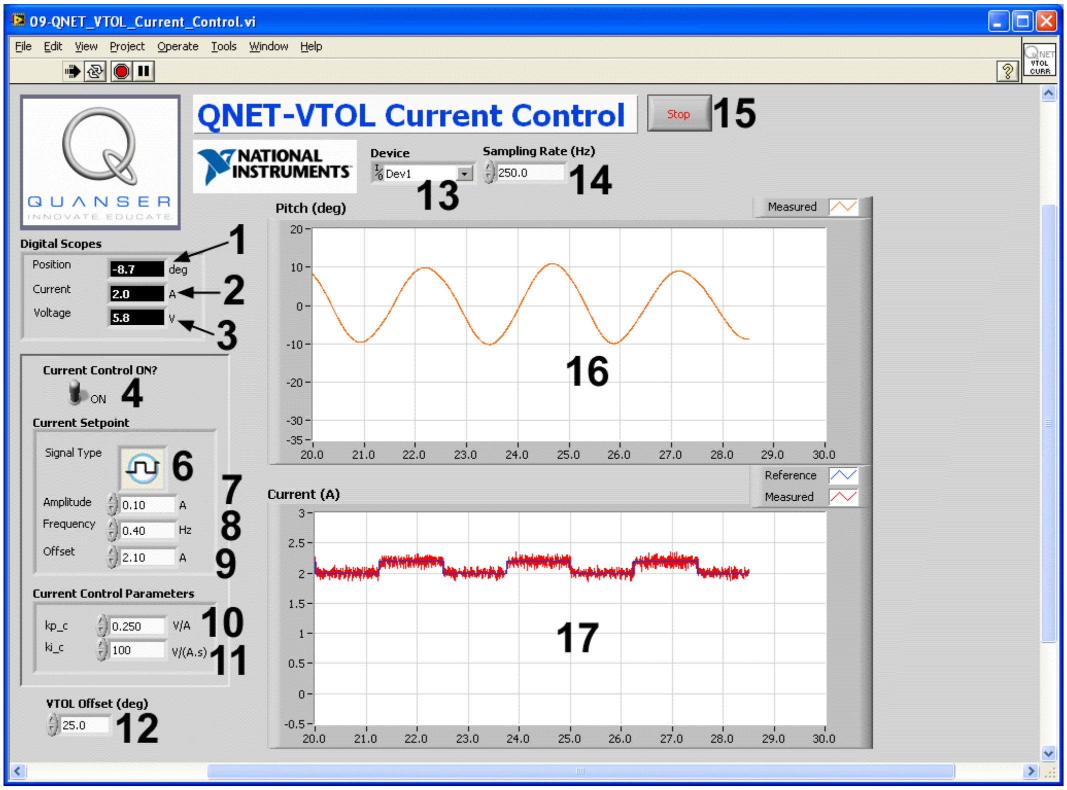


Figure 5.1: QNET-VTOL Current Control VI when in open-loop current mode

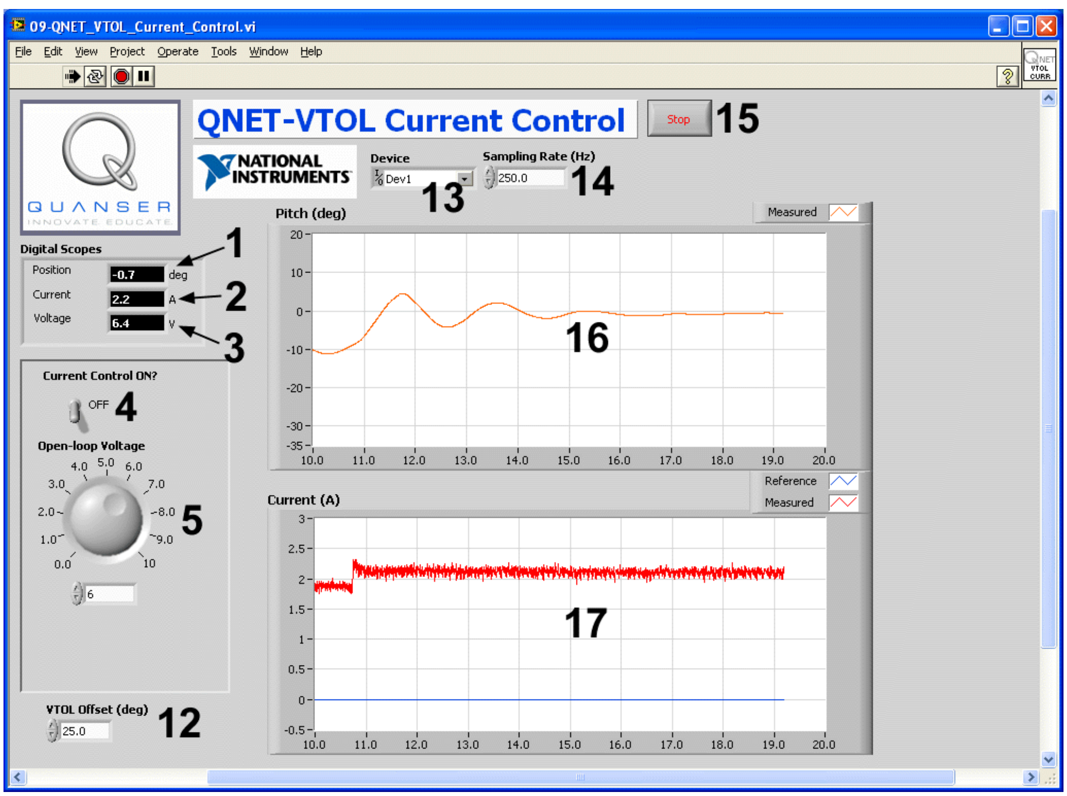


Figure 5.2: QNET-VTOL Current Control VI when in open-loop voltage mode

ID #	Label	Symbol	Description	Unit
1	Position	θ	Pitch position numeric display	deg
2	Current	I_m	Motor armature current numeric display	A
3	Voltage	V_m	Motor input voltage numeric display	V
4	Current Control ON?		Turns current control on and off	
5	Open-loop Voltage		Input motor voltage to be fed	V
6	Signal Type		Type of signal generated for current reference	
7	Amplitude		Current setpoint amplitude input box	A
8	Frequency	K	Current setpoint frequency input box	Hz
9	Offset	τ	Current setpoint offset input box	A
10	kp_c		Current control proportional gain	V/A
11	ki_c		Current control derivative gain	V·s/A
12	VTOL Offset		Pitch calibration	deg
13	Device		Selects the NI DAQ device	
14	Sampling Rate	ω_m	Sets the sampling rate of the VI	Hz
15	Stop	V_m	Stops the LabVIEW VI from running	
16	Scopes: Pitch	ω_m	Scope with measured (in red) VTOL pitch position	deg
17	Scope: Current	I_m	Scope with reference current (in blue) and measured current (in red)	A

Table 5.2: Components of QNET-VTOL Current Control VI

5.3 Modeling Laboratory VI

This VI is used for model validation and parameter identification and is shown in Figure 5.3. A transfer function is ran in parallel with the actual system and enables users to confirm whether their derived model is correct. Using the LabVIEW System Identification Toolkit, the VTOL Trainer transfer function model can be identified automatically by collecting the measured stimulus (i.e. current) and response (i.e. measured pitch angle) signals and specifying the order of the transfer function process model. The main components of the QNET VTOL Modeling VI front panel are listed and described in Table 5.3. Every element is given an ID number which is used to uniquely identify the VI components in Figure 5.3.

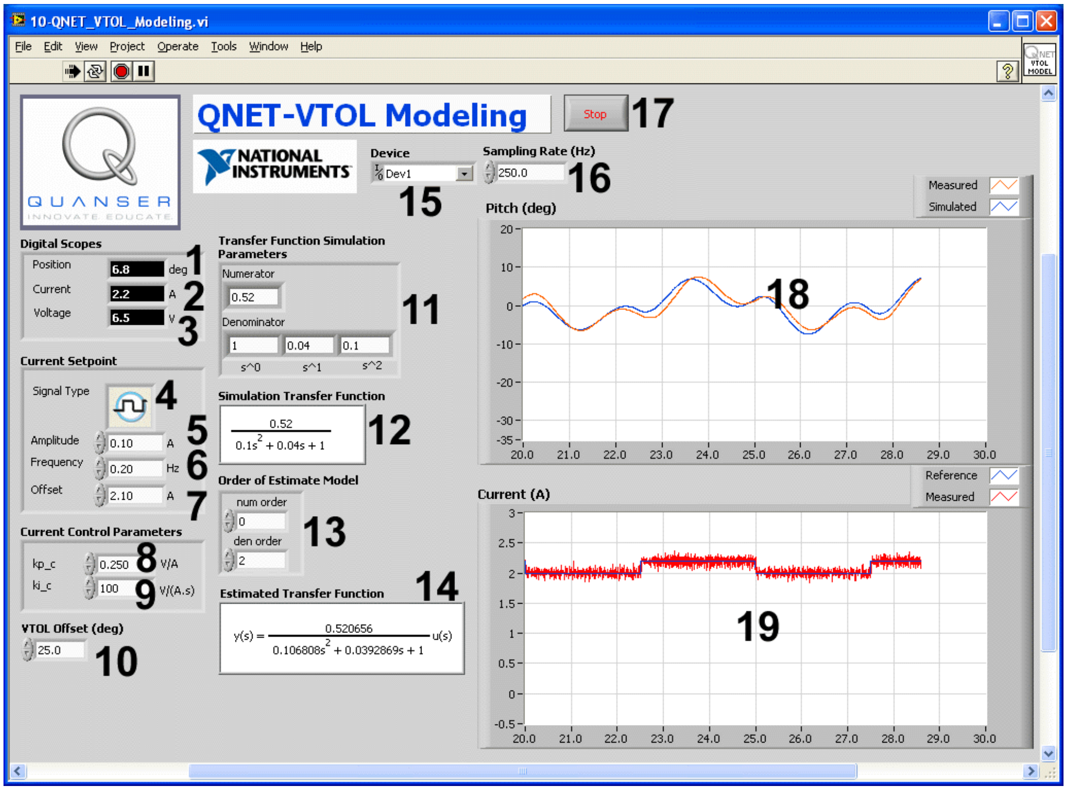


Figure 5.3: QNET-VTOL Modeling VI

ID #	Label	Symbol	Description	Unit
1	Position	θ	Pitch position numeric display	deg
2	Current	I_m	Motor armature current numeric display	A
3	Voltage	V_m	Motor input voltage numeric display	V
4	Signal Type		Type of signal generated for the current reference	
5	Amplitude		Current setpoint input box	A
6	Frequency		Current setpoint frequency input box	Hz
7	Offset		Current setpoint offset input box	A
8	kp_c	$k_{p,c}$	Current control proportional gain	V/A
9	ki_c	$k_{i,c}$	Current control integral gain	V$cdot$s/A
10	VTOL Offset		Pitch calibration	deg
11	Transfer Function Simulation Parameters		Transfer function used for simulation	
12	Simulation Transfer Function		Displays the transfer function begin simulated	
13	Order of Estimated Model		Order of transfer function to be estimated using the *System Identification Toolkit*	
14	Estimated Transfer Function		Transfer function estimated using the *System Identification Toolkit*	
15	Device		Selects the NI DAQ device	
16	Sampling Rate		Sets the sampling rate of the VI	Hz
17	Stop		Stops the LabVIEW VI from running	
18	Scope: Pitch	θ	Scope with simulated position (in blue) and measured VTOL pitch position (in red)	deg
19	Scope: Current	I_m	Scope with reference current (in blue) and measured current (in red)	A

Table 5.3: QNET VTOL Modeling VI Components

5.4 Flight Control Laboratory VI

The QNET VTOL Flight Control VI runs the PID-based cascade control system, which is described in Section 2.1.1, to control the position of the VTOL pitch. Table 5.4 lists and describes the main elements of the QNET VTOL Flight Control VI and every element is uniquely identified by an ID number in Figure 5.4.

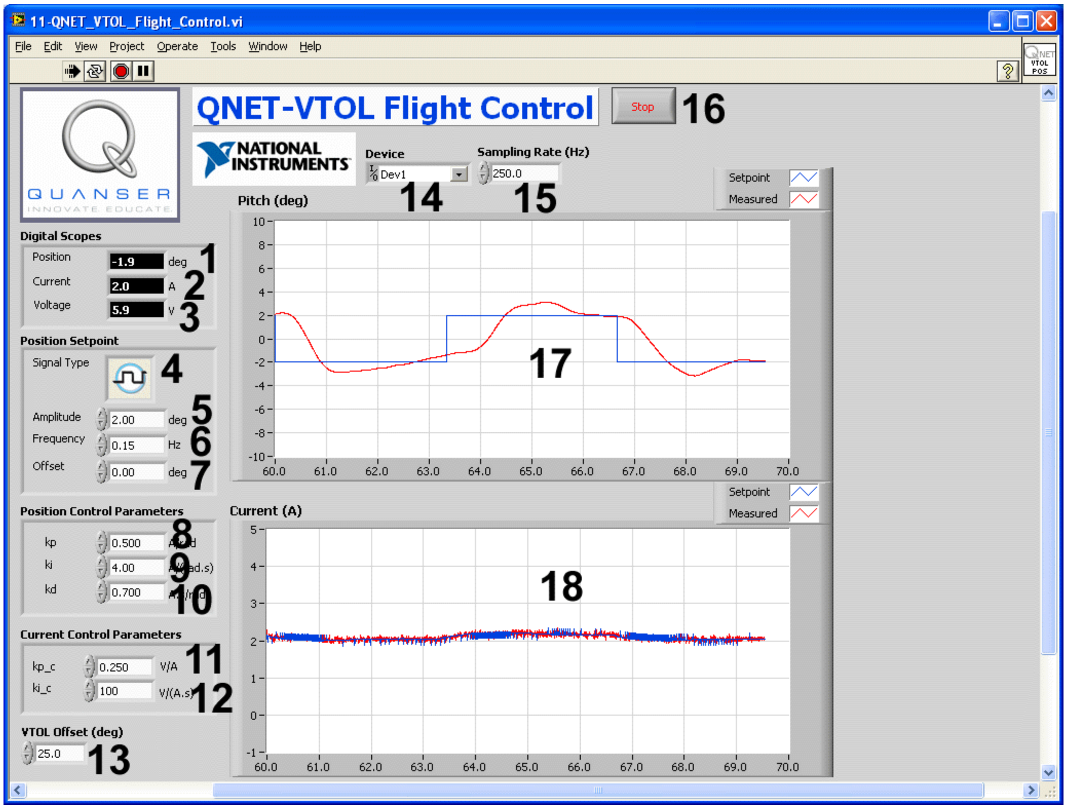


Figure 5.4: QNET VTOL Flight Control VI

ID #	Label	Symbol	Description	Unit
1	Position	θ	Pitch position numeric display	deg
2	Current	I_m	Motor armature current numeric display	A
3	Voltage	V_m	Motor input voltage numeric display	V
4	Signal Type		Type of signal generated for the current reference	
5	Amplitude		Pitch setpoint input box	A
6	Frequency		Pitch setpoint frequency input box	Hz
7	Offset		Pitch setpoint offset input box	A
8	kp	k_p	Position control proportional gain	A/rad
9	ki	k_i	Position control integral gain	A/(rad·s)
10	kd	k_d	Position control derivative gain	A·s/rad
11	kp_c	$k_{p,c}$	Current control proportional gain	V/A
12	ki_c	$k_{i,c}$	Current control integral gain	V$cdots$/A
13	VTOL Offset		Pitch calibration	deg
14	Device		Selects the NI DAQ device	
15	Sampling Rate		Sets the sampling rate of the VI	Hz
16	Stop		Stops the LabVIEW VI from running	
17	Scope: Pitch	θ	Scope with reference position (in blue) and measured VTOL pitch position (in red)	deg
18	Scope: Current	I_m	Scope with reference current (in blue) and measured current (in red)	A

Table 5.4: QNET VTOL Flight Control VI Components

6 LAB REPORT

This laboratory contains three groups of experiments, namely,

1. Current Control,
2. Modeling, and
3. Flight Control.

For each experiment, follow the outline corresponding to that experiment to build the *content* of your report. Also, in Section 6.4 you can find some basic tips for the *format* of your report.

6.1 Template for Content (Current Control)

I. PROCEDURE

1. *Finding Resistance*
    - Briefly describe the main goal of the experiment.
    - Briefly describe the experimental procedure in Step 6 in Section 2.3.
2. *Qualitative Current Control*
    - Briefly describe the main goal of the experiment.
    - Briefly describe the experimental procedure in Step 7 in Section 2.4.
    - Effect of eliminating integral gain in Step 7 in Section 2.4.
    - Effect of eliminating proportional gain in Step 9 in Section 2.4.
3. *Current Control Design*
    - Briefly describe the main goal of this experiment.
    - Briefly describe the experimental procedure in Step 7 in Section 2.5.2.

II. RESULTS
Do not interpret or analyze the data in this section. Just provide the results.

1. Current response plot from step 7 in Section 2.4.
2. Current response plot from step 9 in Section 2.4.
3. Current response plot from step 7 in Section 2.5.2.
4. Provide applicable data collected in this laboratory from Table 2.2.

IV. CONCLUSIONS
Interpret your results to arrive at logical conclusions for the following:

1. How does the current response with tuned gains compare to the qualitative responses in Step 7 of Section 2.5.2?

6.2 Template for Content (Modeling)

I. PROCEDURE

1. *Measure the Equilibrium Current*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experiment procedure in Step 9 in Section 3.3.
2. *Find Natural Frequency*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experiment procedure in Step 7 in Section 3.4.
3. *Model Validation*
   - Briefly describe the main goal of the experiment.
   - Briefly describe creating the model in Step 8 in Section 3.5.2.
4. *Using the System Identification Tool*
   - Briefly describe the main goal of the experiment.
   - Briefly describe creating the model in Step 6 in Section 3.6.

II. RESULTS
Do not interpret or analyze the data in this section. Just provide the results.

1. Pitch and current response from step 9 in Section 3.3.
2. Equilibrium current step response from step 7 in Section 3.4.
3. Transfer function response from step 9 in Section 3.4.
4. Provide applicable data collected in this laboratory from Table 3.1.

III. ANALYSIS
Provide details of your calculations (methods used) for analysis for each of the following:

1. Natural frequency determination from Step 7 of Section 3.4.
2. How well does the simulation match the measured signal in Step 8 of Section 3.5.2?
3. Calculation of the model parameters from the identified transfer function in Step 11 of Section 3.6

IV. CONCLUSIONS
Interpret your results to arrive at logical conclusions for the following:

1. How is the simulation matching the measured signal compared to the transfer function with manually estimated parameters in Step 9 of Section 3.4?
2. How do the generated parameters compare to the manually estimated parameters in Step 11 of Section 3.6?

6.3 Template for Content (Flight Control)

I. PROCEDURE

1. *PD Steady-State Analysis*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experimental procedure in Step 9 in Section 4.3.2.
2. *PID Steady-State Error Analysis*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experimental procedure in Step 3 in Section 4.4.2.
3. *PID Control Design*
   - Briefly describe the main goal of this experiment.
   - Briefly describe the experimental procedure in Step 8 in Section 4.5.2.

II. RESULTS
Do not interpret or analyze the data in this section. Just provide the results.

1. Pitch response plot from Step 9 in Section 4.3.2.
2. PID response plot from Step 3 in Section 4.4.2.
3. PID response plot from Step 8 in Section 4.5.2.
4. Provide applicable data collected in this laboratory from Table 4.1

III. ANALYSIS
Provide details of your calculations (methods used) for analysis for each of the following:

1. VTOL Trainer response characteristics in Step 9 in Section 4.5.2.
2. Improvements to the flight controller in Step 10 in Section 4.5.2.

IV. CONCLUSIONS
Interpret your results to arrive at logical conclusions for the following:

1. How does the measured steady state PD error compare to the computed value in 9 in Section 4.3.2?
2. How does the measured steady state PID error compare to the computed value in 3 in Section 4.4.2?
3. Are the VTOL Trainer response specifications satisfied in Step 9 of Section 4.5.2?

6.4 Tips for Report Format

PROFESSIONAL APPEARANCE

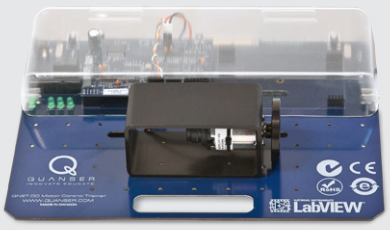
- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

REFERENCES

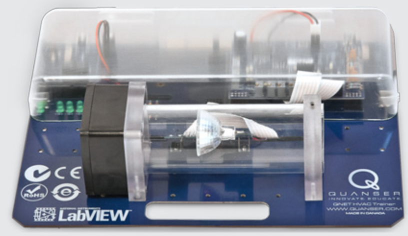
[1] Quanser Inc. *QNET VTOL Control Trainer User Manual*, 2011.

Six QNET Trainers to teach introductory controls using NI ELVIS

QNET DC Motor Control Trainer
teaches fundamentals of DC motor control

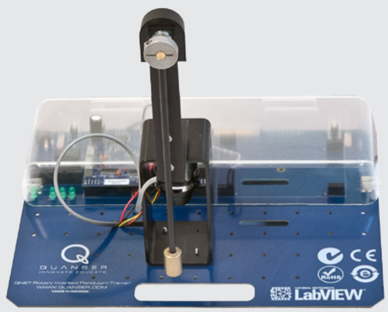


QNET HVAC Trainer
teaches temperature (process) control



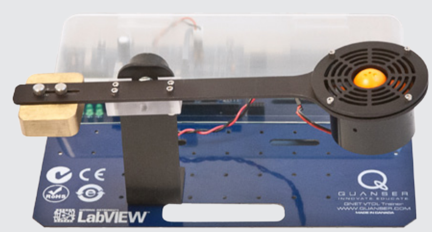
QNET Mechatronic Sensors Trainer
teaches functions of 10 different sensors

QNET Rotary Inverted Pendulum Trainer
teaches classic pendulum control experiment



QNET Myoelectric Trainer
teaches control using principles of electromyography (EMG)

QNET VTOL Trainer
teaches basic flight dynamics and control



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